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DESIGN, ANALYSIS, FABRICATION AND TESTING OF MINI PROPELLER FOR MAVS

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ABSTRACT

Design, analysis, fabrication and testing of propeller for low Reynolds number applications with proper matching of propeller characteristics with that of mini electric brushless motors with appreciable increase in efficiency for use in micro air vehicles is very challenging work. A two bladed 6 inch diameter, variable speed, fixed pitch propeller, design, analysis, fabrication and tests were carried out in National Aerospace Laboratories. In view of its geometry and low Reynolds number in the range of 10,000 to 50,000, extensive use of computational tools like FLUENT, XFLR5 are used to characterize the airfoil in 2D environment and also its thrust, torque and power were evaluated using FLUENT in 3D environment. Overall performance was also evaluated using indigenously built test set up for measuring the thrust and power using low speed wind tunnel of NAL. Structural analysis was carried out using ANSYS program. In view of its thin profile and to have good accuracy, initially the propeller was fabricated using rapid prototyping (RPT) using Acrylonitrile butadiene styrene (ABS-M30) material and the same was used to evaluate the static thrust and wind tunnel testing. Subsequently the propeller was fabricated using CFRP material and the necessary aluminum mould was machined using 3 -Axis NC machine. Computed values were compared with the results from static and wind tunnel tests in uninstalled condition. The computed values are fairly in good agreement with the test results. Flight tests were carried out using NAL designed micro air vehicle "Black- Kite".

Key Words: Micro air vehicle, Propeller design, Propeller analysis, Low-Reynolds number airfoil, propulsive efficiency, Static thrust, Figure of merit.

NOMENCLATURE

A	Area of propeller disc, m^2	α	Angle of attack, deg
B	Number of Blades	β	Pitch angle, deg
C	Chord of Airfoil, m	ρ	Density, kg/m^3
D	Diameter of propeller, m	Ω	Angular velocity, rad/s
I	Current, Amps	μ	Viscosity, m^2/s^2
J	Advance ratio	η	Efficiency
N	Rotational speed, rpm	σ	Solidity ratio
n	Rotational speed, rps		
P	Pitch, Power, Pressure in accordance	C_d	Coefficient of drag
Q	Torque, N-m	C_l	Coefficient of lift
R	Tip radius of the propeller, m	C_p	Coefficient of power
r	Sectional radius, m	C_q	Coefficient of torque
T	Thrust, N or grams	C_t	Coefficient of thrust
V	Velocity, m/s		
FOM	Figure of Merit		

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1. INTRODUCTION

National Aerospace Laboratories (NAL) is having major program to develop Micro Air Vehicles (MAVs). Thrust requirements of MAV's are provided using different propulsive systems, namely high pressure micro-jets or propellers. Commercially available propellers manufacturer does not share the design, aerodynamic and structural details with the end users. Design of propeller for low Reynolds number applications with proper matching of propeller characteristics with that of small, light weight electric motors with appreciable increase in efficiency is very challenging work. Worldwide miniaturization and continues improvement in efficiency of electrical brushless motors are addressed vigorously. Airfoil designed for higher Reynolds numbers are highly inefficient at low Reynolds numbers. Lower flight velocity combined with the lower altitude and massive flow separation makes it more inefficient. The present power plant configuration of NAL MAV propulsion system is battery driven miniature motor and propellers. From the basic configuration for smooth hand launch, it is defined that the maximum weight of NAL micro air vehicle having fixed wing would be limited to 300gms with a minimum thrust requirement of 120gms at takeoff, 40 gms at cruise and thrust to weight ratio of 0.40. This paper describes the design, analysis, fabrication and testing of miniature propeller for NAL MAV's. Literature survey and work carried out else-where indicate that Eppler-193 airfoil is highly prospective candidate airfoil for the above applications [1, 2, 3].

2. METHODOLGY

Overall geometry of a propeller is limited by the thrust requirement or the power availability and rotational speed by its centrifugal stresses as well as tip Mach number. A two bladed 6 inch diameter, variable speed, fixed pitch propeller was designed. Eppler-193 was chosen for most part of the span of the propeller and NACA 66-021 was chosen near the hub section to provide sufficient strength. Two blades are chosen in comparison to three blades on slightly higher efficiency and weight consideration thou one can get lower thrust. The twist and chord distribution shown in were arrived using minimum induced loss method to give required thrust at design condition. Figure of Merit (FOM) is the ratio of induced power to power available for the propeller. FOM, which gives a good indication of the propellers performances, if the geometry or the diameters are same, was used to ascertain the performance with that of commercially available propellers [4]. Apart from this, overall effectiveness of the propellers was evaluated using the thrust generated by the propellers, propellers weight, power consumed by the motor and motor weight. Mainly four parameters were used in evaluating the mini propeller performance, they are efficiency parameter (Thrust/Watt of input power), weight effectiveness parameter {Thrust/ gram of weight (Propeller + motor)}, endurance of flight parameter (Time/Watt of power consumed) and safety parameter (structural integrity and reliability) [4]. CAD model generated was used in aerodynamic analysis, structural analysis and fabrication. Computational tools like FLUENT with k-ε, XFLR5 are used to obtain the drag polar of the airfoil in 2D environment and FLUENT in 3D environment for thrust, torque and power. Structural analysis was carried out using ANSYS program. Fabrication criticality due to its geometry and size, RPT process with ABS material and subsequently molding process for CFRP material were made use of. A specially designed test setup was used to evaluate static thrust and thrust at different free stream velocities in the low speed wind tunnel of NAL.

3. PROCEDURE

The baseline design was carried out using the thrust requirement at design condition and the blade geometry using minimum induced loss method [5, 6]. Figure 1 show the propeller blade geometry and Reynolds number at various sections. NACA 66-021 profile was chosen up to 30% of the blade height and Eppler-193 was chosen for rest of the span.

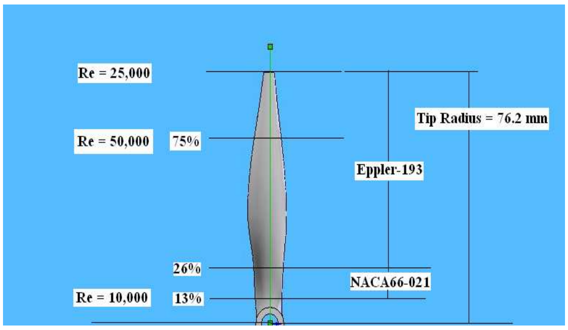

Figure 1. Profile distributions along the Blade Span of NAL MAV PR 01

Figure 2a and 2b shows the chord and the twist distribution along the span of the propeller blade. Maximum chord is taken at 40% of the blade height.

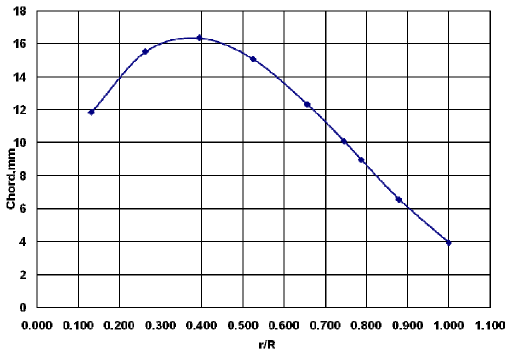

Figure 2a. Chord distribution

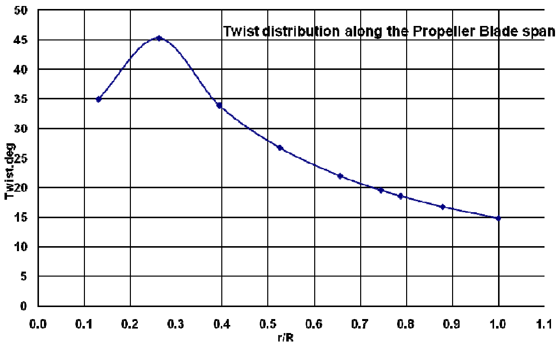

Figure 2b. Twist distribution

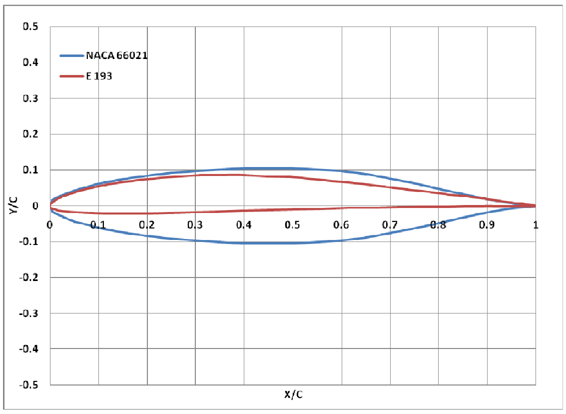

Figure 3. Comparison of profiles used in NAL MAV PR 01

Figure 3 show the NACA 66-021 and Eppler-193 profiles. Not much experimental data available for these low Reynolds number airfoils. To characterize Eppler-193 aerofoil FLUENT and XFLR5 codes are used. The values obtained by these codes were compared with available experimental results at Reynolds number of 307,800.

Figure 4 shows the drag polar computed using FLUENT, XFLR5 and the experimental results [2] at Reynolds number of 307,800 for Eppler-193 profile.

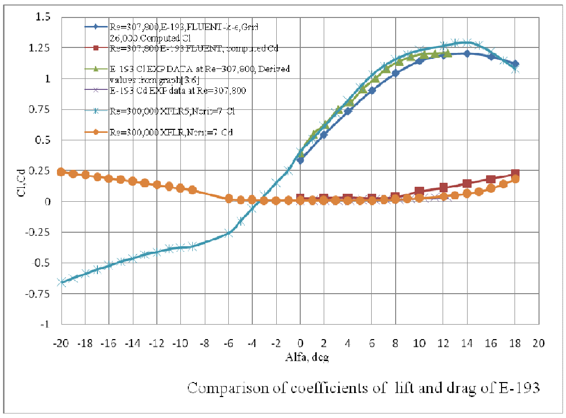

Figure 4. Comparison of coefficients of lift and drag of E-193

XFLR5 values are slightly higher and FLUENT values are slightly lower than Experimental results. Coefficient of drag was predicted from FLUENT is higher in comparison to XFLR5 as well as experiment results. In view of propeller blade experiences low Reynolds number flow in the range of 10,000 to 50,000, extensive use of computational tools like FLUENT, XFLR5 are used to characterize the airfoil in 2D environment and also propeller thrust, torque and power were evaluated using FLUENT in 3D environment. Figure 5 and 6 show the drag polar evaluated using XFLR5 at the operating Reynolds number of propeller.

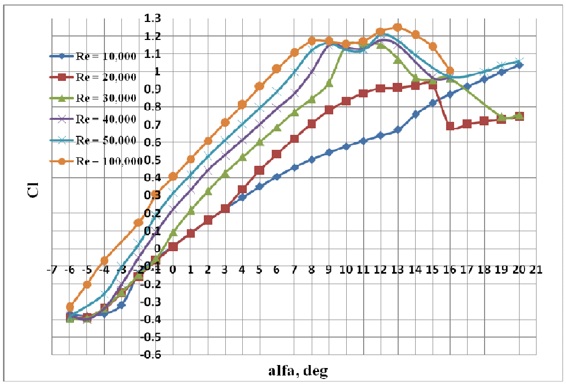

Figure 5. Coefficient of lift at different Re number using XFLR 5 for E-193 profile

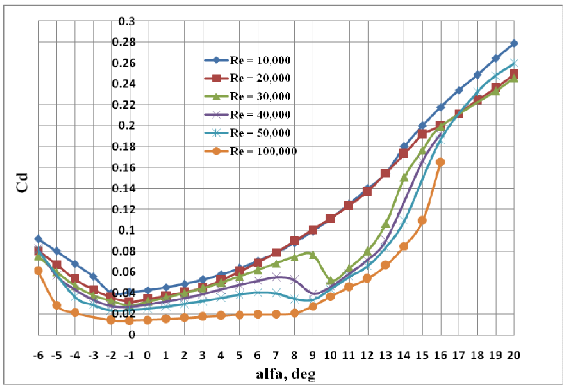

Figure 6. Coefficient of drag at different Re number using XFLR 5 for E-193 profile

Coefficients of lift and drag are used to evaluate the performance of the propeller using Blade Element Moment Theory (BEMT) [6, 7] along with the Prandtl hub tip loss factors. Approach velocity variation in front of the propeller was also taken into consideration. Elemental thrust, torque, power are integrated over the propeller span to get power and thrust. Figure 7, 8, 9 & 10 show the coefficients of thrust, torque, power and propulsive efficiencies at different advance ratios.

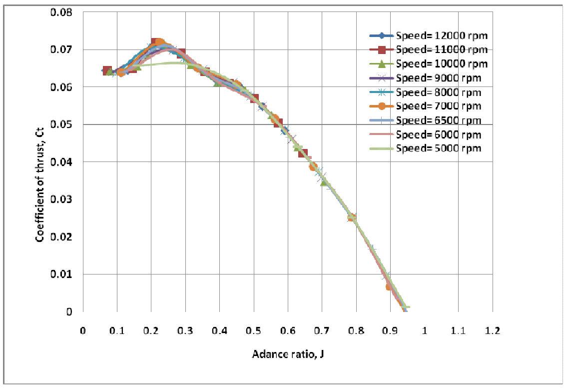

Figure 7. Coefficient of thrust v/s Advance ratios comparison from BEMT

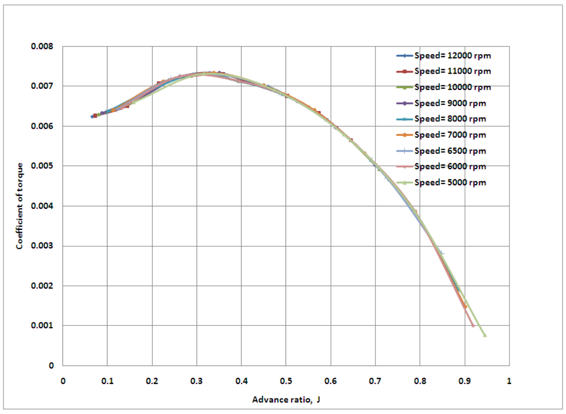

Figure 8. Coefficient of torque v/s Advance ratios from BEMT

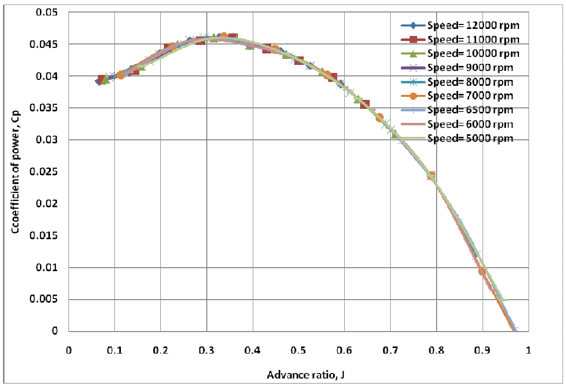

Figure 9. Coefficient of power v/s Advance ratios from BEMT

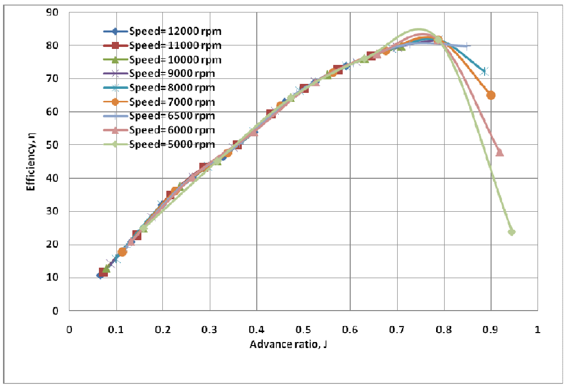

Figure 10. Propulsive efficiency v/s Advance ratios from BEMT

After characterizing the Eppler-193 profile, propeller solid model is created using commercial CAD package ‘Solidworks’.

Figure 11 shows solid model of designed miniature propeller.

Figure 11. Solid model of NAL MAV PR 01 Propeller

CFD analysis: Three dimensional CFD analyses was carried out using commercial CFD code FLUENT on this propeller for different free stream velocities from 2m/s to 16 m/s insteps of 2m/s for different rpm from 6000 rpm to 12000rpm insteps of 1000rpm[9,10]. Figure 12 shows the axial velocity contour obtained from FLUENT near the propeller for cruise condition. The thrust computed from BEMT and CFD were in good agreement at the operating condition of MAV.

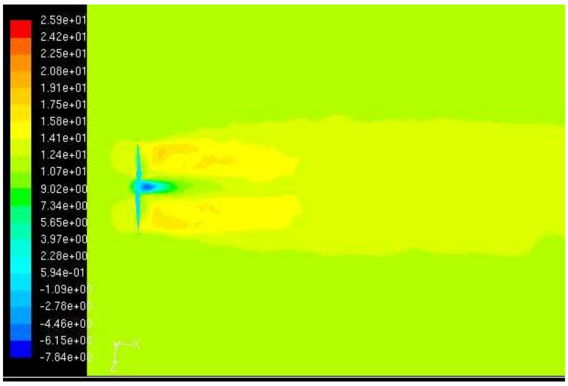

Figure 12. Axial velocity contours near the propeller for cruise condition (8000 rpm and 12 m/s)

Structural analysis: Structural analysis was carried out using ANSYS code. A detail stress analysis was carried out with "carbon fiber reinforced plastic (CFRP)" material for propeller using FEM package to ensure structural integrity [7]. Figure 13 shows finite element model of the propeller and its cross section for clarity. Static nonlinear analysis was carried out in the range of 8000 RPM to 12000 RPM at free stream wind velocity of 12m/s, Material data, boundary condition, thrust distribution and angular velocity were inputs. Analysis was carried out using non-linear geometric option. Analysis show that the bending stress and Von mises stress are of the order of 18.8 MPa to 37MPa at r/R of 0.34 near the hub section on suction surface and is well within the ultimate value of 100 MPa. Figure 14 shows the bending stress distribution on propeller.

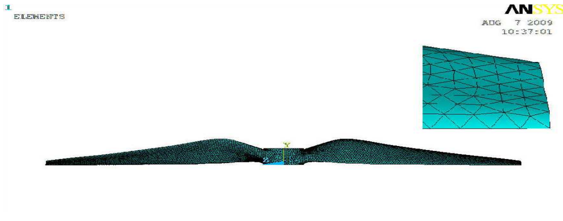

Figure 13. Finite element model of the propeller

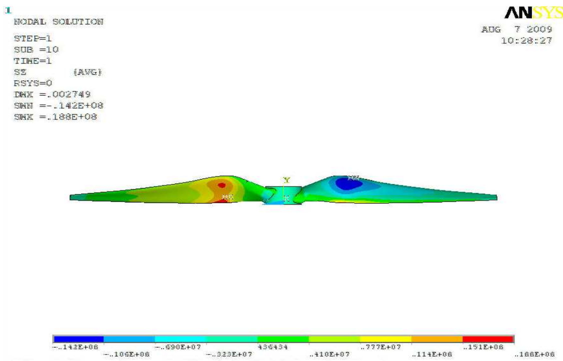

Figure 14. Bending stresses obtained from stress analysis on NAL-MAV PR01

Fabrication: Propeller was fabricated using RPT process with ABS-M30 material as shown in Figure 15 and the same was tested for static thrust and flight condition performance evaluation in the low speed wind tunnel using test setup developed at National Aerospace Laboratories. During the flight test, the propellers blades fabricated using RPT process could not withstand harsh landing and ground impact, resulting in blade failure**.**

Figure 15. RPT Propeller

Subsequently the propeller was fabricated using CFRP material and the necessary aluminum mould was machined using 3 -Axis NC machine as shown in Figure 16 and 17. Due care was taken to avoid the blow holes in the propellers and the propellers were statically balanced using static balancing machine.

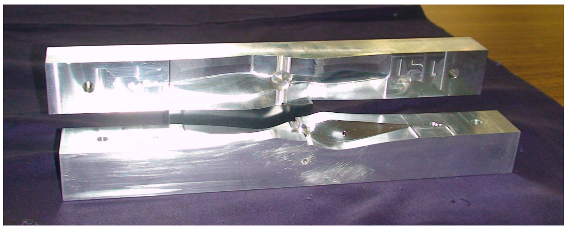

Figure 16. Aluminum mould of the propeller

Figure 17. CFRP Propeller

Test set up: A portable test setup was built indigenously using beam type load cell having capacity up to 600gms for measuring thrust and mini brushless electric motors for powering the propellers has shown in Figure.18.

Figure 18. Test set up in low speed wind tunnel for testing propeller-motor combinations

Thrust, power, rotational speeds, weight of the propeller and motors were measured [4,8]. In the present test set up direct torque measurement was not envisaged. The test set up could be used to measure the static thrust, motor input power in terms of voltage and current, and thrust in low speed wind tunnel at different flight velocities.

Performance Evaluation: Overall performance was evaluated using indigenously built test set up for measuring the thrust and power using low speed wind tunnel of NAL in uninstalled condition. Tests were carried out for different free stream velocities ranging from 2 to 18 m/s in steps of 2 m/s for the speed range of 4000 rpm to 12000 rpm in steps of 1000 rpm. Figure 19 show the comparison of coefficient of thrust v/s advance ratio obtained from CFD, Experiment and BEMT for design speed 8000rpm.

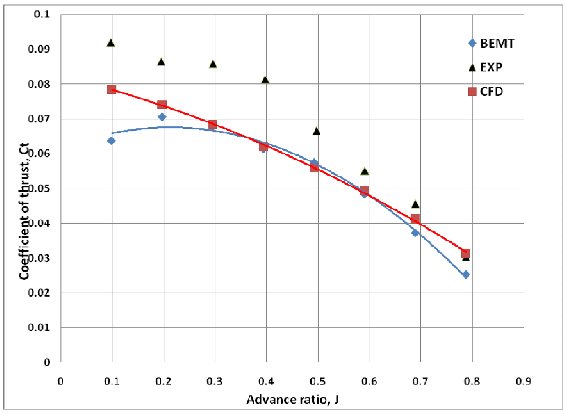

Figure 19. Comparison of coefficient of thrust vs advance ratios for CFD, Experiment and BEMT

Figure 20 and 21 shows the comparison of experimental results and 3D CFD values for the operating range of thrust and power v/s advanced ratios.

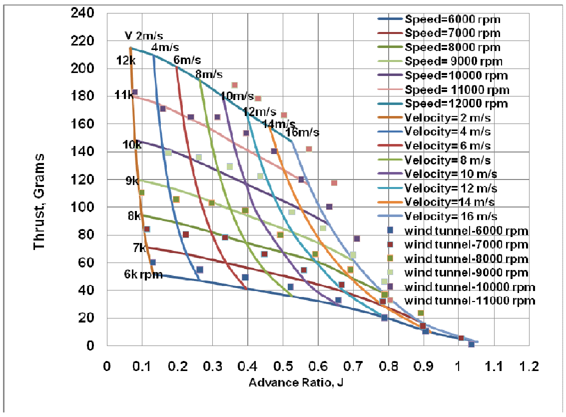

Figure 20. Comparison of CFD results with the experimental results for Thrust v/s Advance ratio

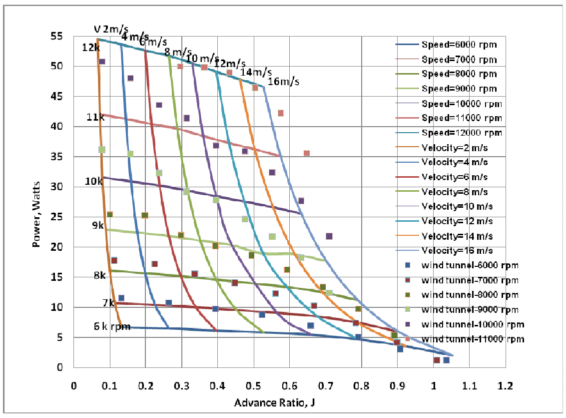

Figure 21. Comparison of CFD results with the experimental results for Power v/s Advance ratios

4. RESULTS AND DISCUSSION

The thrust measured at lower air velocities are slightly higher than the computed as well as calculated from BEMT method. However thrust measured at very close to operating conditions of MAV are in good agreement. In the absence of validated drag polar at lower air velocities and Reynolds numbers could have lead to calculation of lower thrust. However the experimental results have conclusively shown that the requirements of thrust at take-off and cruise conditions were met. The propulsive efficiencies are greater than 76% at the design condition. The brushless mini motor efficiencies were taken from the manufacturer catalogue as such the overall efficiency of propeller-motor combinations was close to 56%. It is very prudent to measure thrust, torque and speed simultaneously of the propulsive system to obtain accurate efficiencies. The methodologies developed for evaluating overall effectiveness parameters of propeller-motor combinations were consistent and reliable. Fabrication methodologies developed and selection of material for mini propeller was a major step in realizing the product with good accuracies. Structural analysis carried out using ANSYS program shows a good margin of structural strength and a factor of safety greater than 3. Though all the tests on propeller were carried out at uninstalled conditions, Flight test carried out using NAL designed micro air vehicle Black- Kite was successful with good performance.

5. CONCLUSIONS

Methodologies developed for design, fabrication and testing of miniature propeller to have a good performance in the low Reynolds number operating condition of MAVs of 300mm class were accomplished. Extensive use of commercially available CFD tools as well as empirical equations were highly useful to hasten the process and in realizing the mini high performance propellers. Methodologies developed for selection of propeller – motor combinations were effective and reliable. Substantial improvement in measurement of propulsive efficiencies could be made by simultaneously measuring thrust, torque and rotational speeds. Work carried out was a major milestone in development of indigenous micro air vehicles.

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